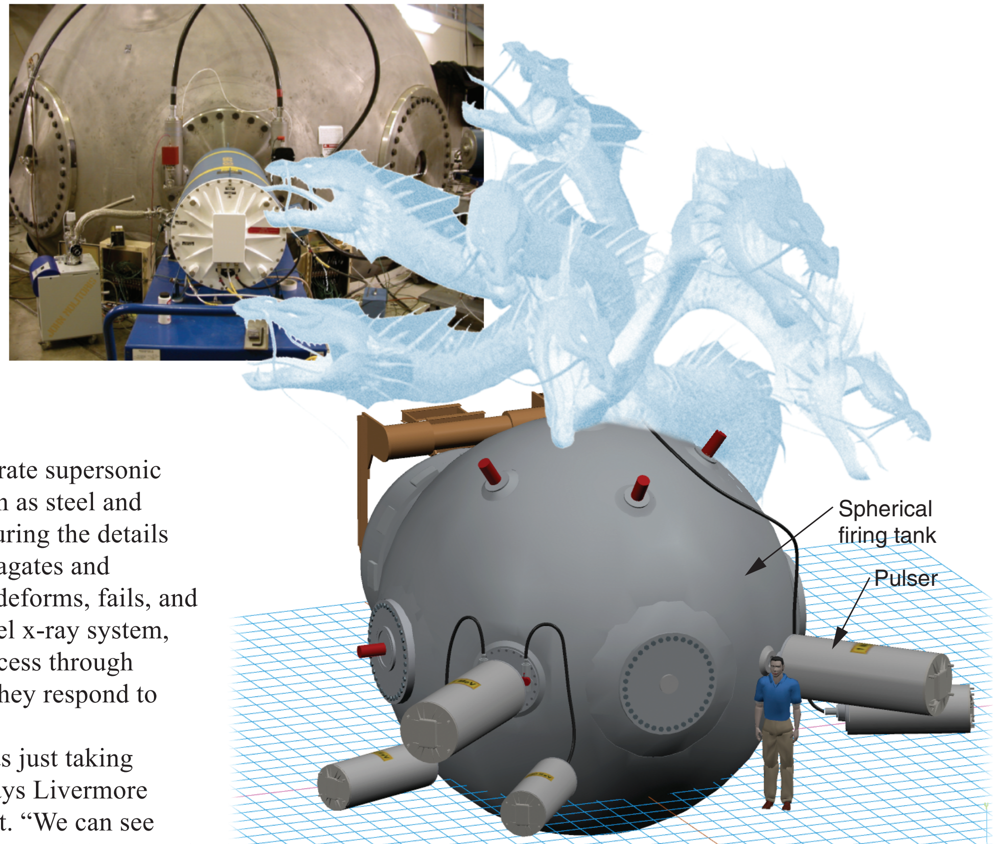
The Shocking Truth about Detonations and Metals



The current configuration of Hydra, Livermore's multichannel x-ray system, has two 1-megaelectronvolt super pulsers, one 450-kiloelectronvolt super pulser, and two 450-kiloelectronvolt pulsers. The fifth channel projects a view that allows scientists to determine if the experiment breaks cylindrical symmetry. The rendering of Hydra shows all five pulsers. Above left is a photo of the system.

WHEN high explosives detonate, they generate supersonic shock waves that can cause materials such as steel and aluminum to deform and ultimately fail. Capturing the details of this dynamic process—how the shock propagates and interacts with materials and how the material deforms, fails, and fragments—is tricky. Livermore's multichannel x-ray system, called Hydra, provides a window into this process through exquisitely detailed radiographs of metals as they respond to detonations and the intense shocks generated.

"People usually think of imaging systems as just taking 'pictures,' but Hydra provides much more," says Livermore physicist John Molitoris, who leads the project. "We can see through to the event of interest, observe density variations, track a process, and measure velocities." Hydra can record a sequence of images, capturing a dynamic process as it evolves over time and showing, for example, how a material responds to intense shock loading. The system can also record multiple images at one time but from various angles, allowing scientists to reconstruct a detailed three-dimensional snapshot at one moment in the process. This approach allows scientists to examine metal fragments as they are produced and ejected from the original component.

With Hydra's radiographs, Livermore researchers now have access to never-before-measured data on the physical characteristics, velocity, deformation history, and fragmentation of shocked metals. They also have discovered features and phenomena not predicted by materials models.

The Many-Headed Hydra

Named for the many-headed monster in Greek mythology, the multichannel system is located in Livermore's High Explosives Applications Facility (HEAF). In its present configuration, Hydra has five x-ray channels that image dynamic experiments inside a 4.9-meter-diameter spherical firing tank. The three channels driven by super pulsers allow Hydra to generate a higher x-ray flux than commercial pulsers, resulting in higher contrast radiographic images over a wider range of material densities. The fourth and fifth channels are driven by standard 450-kiloelectronvolt x-ray pulsers, which will be upgraded to new super pulsers. The fourth channel increases Hydra's time sequence capabilities, and the fifth channel gives a "different view" according to Jan Batteux, lead technical associate for Hydra. "Channel five projects a view that allows us to determine if the experiment is breaking cylindrical symmetry," says Batteux.

Not only can operators change the timing of x-ray flashes, they also can adjust the system's contrast so it images shock processes in various materials from aerogels to steel and possibly even tantalum. Hydra's 25-nanosecond time resolution can "freeze" any shock process caused by detonation. Spatial resolution is better than 1 millimeter and can exceed 0.1 millimeter, depending on the level of contrast.

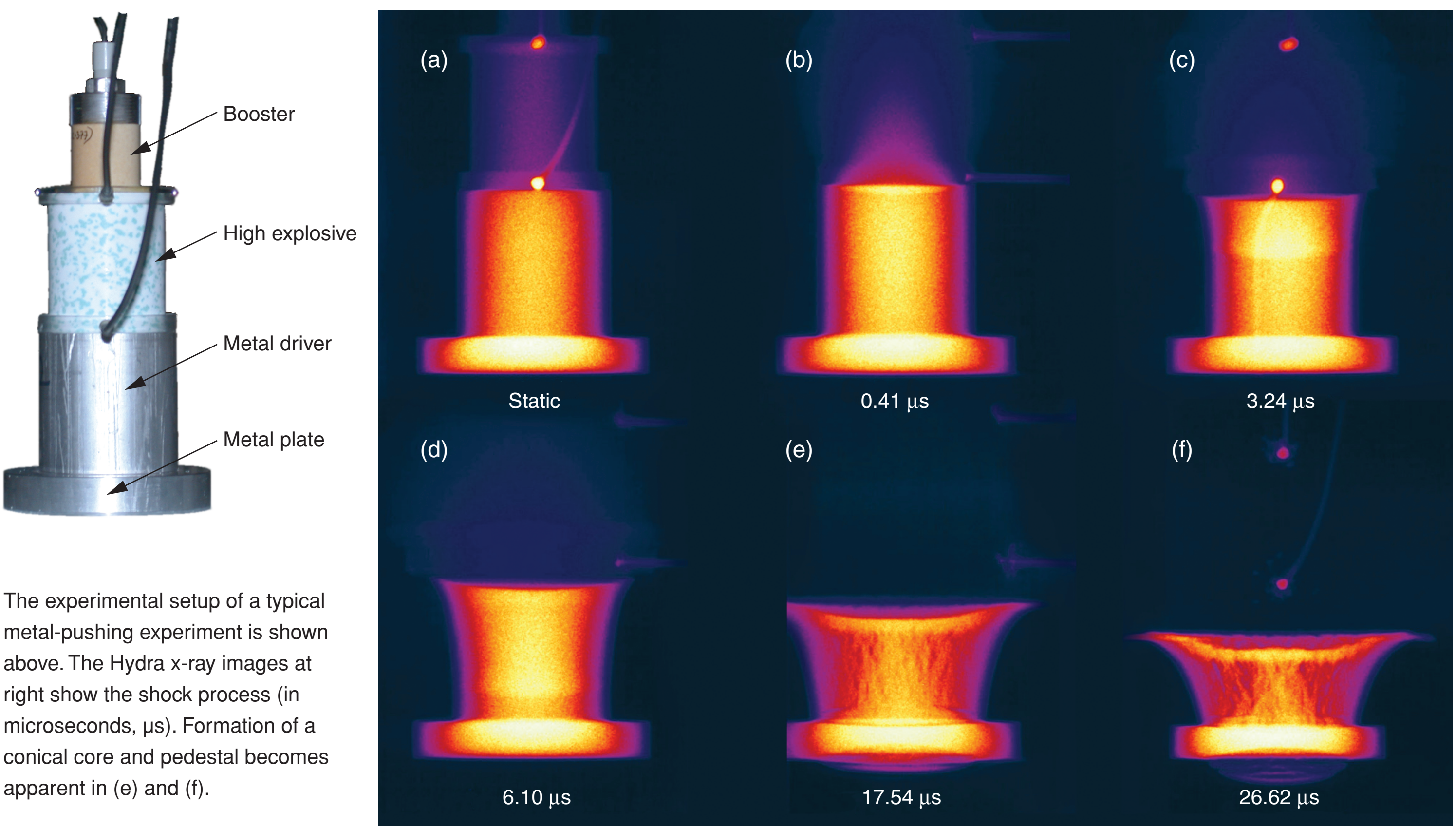
Shock and Spall

Hydra became operational in summer 2004, and since then, it has provided valuable information for validating computer models. (See *S&TR*, December 2004, pp. 22–25.) Experimental results from Hydra are critical to the model validation effort because the system can precisely measure a material's response and velocities. These detailed results can then be compared to a code's predictions, which show scientists whether a code accurately models the phenomena. "Modern computer simulations generate predictions in vivid detail," says Molitoris, "but to validate and improve the codes, we need diagnostics such as Hydra that can record test data of equal detail."

Livermore scientist Raul Garza and Molitoris designed a series of metal-pushing experiments (MPX) to investigate how bulk metal responds to shock, including the effects of spallation. "Spallation is the prompt ejection of material from the outer surface of a shocked metal," says Garza. When a shock wave hits a metal object, much of it passes through the object. But some of it reflects back and forth from the surfaces, like an echo, causing the metal to spall. Spall especially affects the state of the residual metal and how it finally fragments. The situation is further complicated by the metal chunks or particulates injected into the region being shocked.

In the MPX setup, the detonating explosive main charge imparts a known shock to a solid cylindrical metal driver. The driver delivers the shock to a metal plate, which can spall. The driver's length can be varied to adjust the strength of the shock transmitted to the plate: the longer the driver, the weaker the shock. When the metal plate spalls, it creates a spall disk that is ejected from the bottom. Hydra radiographs capture in detail how the metal plate and driver respond to the shock wave.

"Our goal was to measure the deformation history of the disk, the possible formation of the spallation region, and if spall occurred, the ejection velocity. But we learned much more," says Molitoris. Late-time response of the driver yielded unexpected results. Both deformation and velocity are easily quantified by time-sequence radiography, where a change in position is measured as a function of time. However, the Hydra images showed the response of the *entire* component as a function of time, not just the spall region. The high-resolution time-sequence data clearly showed not only the details of the spallation process but also fragmentation and residual structure of the metal driver. In particular, a conical core section formed in the driver component of the experiment and a pedestal formed at the base of the driver where the shock was transmitted to the spall disk.



The experimental setup of a typical metal-pushing experiment is shown above. The Hydra x-ray images at right show the shock process (in microseconds, µs). Formation of a conical core and pedestal becomes apparent in (e) and (f).

"None of the codes predicted this particular response to the shocks," says Molitoris. "In fact, when we first looked at the images, we didn't believe the driver was breaking up in this manner." Computer colorization added by Livermore scientist Hank Andreski, who also designed Hydra's computer control system, enhanced the structure forming inside the shocked driver.

The next step was to recover the residual pieces of the driver to confirm the radiographic data. In following experiments of the MPX series, the team did, indeed, recover conical cores along with the spall and ejecta disks. "The data gathered from the radiographs allowed us to quantify the way this component fails and breaks up," says Molitoris. "We saw something unexpected and confirmed it, elevating our confidence in Hydra. That's the beauty of high-fidelity experimental data; we get a clear glimpse of the truth. Then, of course, we have to understand it." Understanding a metal's response to high-explosives-generated shock waves is important to work for the Department of Energy and the Department of Defense. Data generated from MPX are helping scientists improve codes used to model shocked metals.

Subsequent metallurgy performed on the recovered pieces showed that the metal forming the pedestal had no voids or rips, but the conical section was clearly a product of violent processes. Metal had ripped away from this section, leaving a jagged brittle cone. According to Molitoris, the cone may be caused by a hydrodynamic backsplash—an effect that is well known in fluid dynamics. In this process, a fluid surface hit by an object (or a drop of liquid) forms a peak in the splash zone, and frequently, a drop of liquid is ejected and falls back to the fluid surface. Some researchers speculate that the peak formed by the backsplash could initiate the formation of the conical core. None of these processes was predicted by the codes.

The Hydra team is also conducting experiments to examine how the type and condition of a metal affects the spallation process. For example, plates of heat-treated steel and brass do not eject whole spallation disks, rather they eject multiple pieces. After spallation, residual metal is very brittle, which significantly changes the final fragmentation process. The team also found that untreated steel and aluminum spall readily, while stainless steel deforms but does not spall under these conditions.

Metals under Extreme Conditions

These experiments are improving scientific understanding of how metal behaves under high pressure and shock conditions. "We can now see aspects of dynamic metallurgy that no one has predicted," says Molitoris. "With Hydra, we not only see these details frozen in time, but we also can observe the fragmentation process as it evolves. Such time-sequence detail is not available with other diagnostics." In addition, with Hydra's high temporal and spatial resolution and its time-sequence capabilities, scientists can examine fragments as they form, thus eliminating the tedious and time-consuming process of capturing the fragments for further study.

More improvements are planned for Hydra. Senior radiographer Chuck Cook is working on filmless data acquisition, and the team is examining electronic imaging for some experiments so data can be transferred directly to the computer. The major upgrade for Hydra is expanding the system to 10 or 11 x-ray channels, which will increase the time-sequence imaging capabilities.

"The world of shocked metals is violent, fast, and full of twists and turns," says Molitoris. "Freezing this world so we can examine it is our way of getting a glimpse of the truth."

—Ann Parker

This material recovered from a shocked metals experiment was evident in the Hydra image data. (See image [f] in the figure on p. 12).

Key Words: aluminum, fragmentation, high explosive, High Explosives Applications Facility (HEAF), Hydra multichannel x-ray system, metal behavior, shock wave, spall, x-radiography.

For further information contact John Molitoris (925) 423-3496 (molitoris1@llnl.gov).